Radar and Optical Observations of Asteroid 1998 KY26

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Observations of near-Earth asteroid 1998 KY26 shortly after its discovery reveal a slightly elongated spheroid with a diameter of about 30 m, a composition analogous to carbonaceous chondritic meteorites, and a rotation period of 10.7 minutes, which is an order of magnitude shorter than that measured for any other solar system object. The rotation is too rapid for 1998 KY26 to consist of multiple components bound together just by their mutual gravitational attraction. This monolithic object probably is a fragment derived from cratering or collisional destruction of a much larger asteroid.

radar

The population of asteroids in the 10-to-100-meter size range is thought to number ~10^7 in Earth-crossing orbits and ~10^9 in the main belt (1,2). However, only a few dozen several-decameter-sized objects have been discovered, and little is known about their spin states, shapes, compositions, surface characteristics, or interiors, much less their origins and collisional histories. Spacecraft flyby observations of several much larger objects (3) help to constrain the collisional evolution of those objects and the asteroid population as a whole (4), but even for those objects, definitive information about interior configuration (and hence collisional history) is lacking: are they coherent solid rocks or gravitationally bound, multi-component agglomerates?

Here we report observations that provide a detailed look at a sub-100-m solar system object. The discovery of 1998 KY26 was announced on 1 June 1998 (5), one week before it passed 2.10 lunar distances (8.061 x 10^5 km) from Earth. Part of a recently recognized, potentially abundant subpopulation of small near-Earth asteroids (NEAs) (1), it is more accessible to a spacecraft rendezvous than any of the other ~25,000 known asteroids with secure orbits (6).

During 6-8 June 1998 we observed the asteroid with the Goldstone X-band (8510-MHz, 3.5-cm) radar, using waveforms that provided various degrees of resolution in time delay (range) and Doppler frequency (radial velocity). During 2-8 June we observed the asteroid photometrically with the Ondřejov (Czech Republic) 0.65-m telescope, the Steward 0.9-m Spacewatch telescope (Arizona), the Mauna Kea 0.61-m telescope (Hawaii), and the Table Mountain 0.6-m telescope (California), obtaining CCD lightcurves and broad-band colors (7).

The asteroid's rapid spin rate was revealed by extreme Doppler broadening of spatially resolved radar echoes and shortly thereafter was measured precisely by Fourier analysis of time series formed from disk-integrated optical brightness measurements. The echoes' bandwidth B (Hz) satisfies $B = 5.945\, D \cos(\delta) / P$, where P (min) is the instantaneous apparent spin period, D (m) is the width of the plane-of-sky projection of the asteroid's pole-on silhouette, and δ is the subradar latitude. B is at least 11 Hz for all our echo spectra (Fig. 1). Waveforms with time-delay resolution of 125 ns (19 m in range) produced echoes confined to a single range cell, placing an upper limit of 19 m on the asteroid's visible range extent and an upper limit of 40 m on the asteroid's physical range extent (8). Therefore the radar data require $P \leq 22$ min. Our spectra show no prominent asymmetries or features and only subtle bandwidth variations, precluding more precise radar estimation of P. However, analysis of our finest-time-resolution photometric lightcurves (Fig. 2) yields an unambiguous estimate of the synodic period, $P = 10.7015 \pm 0.0004$ min (9).

The average of all known asteroid rotation periods is of order 10 h (10). Among unambiguously determined rotation periods, the shortest period is 136 min for 1566 Icarus (11). 1998 KY26 would need a bulk density of order $39000/P^2$ g cm^{-3} (12) , or about 340 g cm^{-3}, for it to consist of pieces held together just by their mutual gravitational attraction. This asteroid's rapid spin thus reveals it to be a monolithic body bound by tensile strength alone (13).

With the calculated period known, the echo spectra could be inverted (14) to estimate the asteroid's shape. The spheroidal model (Fig. 3) has a mean diameter of 26 m/cos(δ). In the absence of prominent variations in echo bandwidth over a 54° sky arc or in lightcurve amplitude over a somewhat larger arc, it is unlikely that any of our observations were within a few tens of degrees of pole-on. The Doppler-based model and the range-resolved data therefore bound 1998 KY26's effective diameter: 20 m $\leq D_{\mathrm{eff}} \leq$ 40 m.

Whereas the asteroid's relative topographic relief is subdued, roughness at centimeter-to-decimeter scales is revealed by the ratio of echo power in the same sense of circular polarization as transmitted (the SC sense) to that in the opposite (OC) sense. A perfectly smooth surface would reflect echoes with SC/OC = 0. 1998 KY26's mean value of SC/OC, 0.5 $\pm$ 0.1, exceeds 90% of the values measured for near-Earth asteroids (15). Because the asteroid is spinning too fast to retain any loose particulate material (a regolith) except perhaps near the poles, most of its surface is exposed, bare rock that has been roughened, probably at least in part by meteoroid bombardment (16).

Our photometry yields an estimate of 1998 KY26's mean, absolute V magnitude, $H = 25.5 \pm 0.3$ (17). That estimate and our D_{eff} interval bound the asteroid's visual albedo (18): $0.05 \leq p_{\mathrm{v}} \leq 0.37$. Cluster analysis of values of p_{v} and visible to near-infrared colors of hundreds of asteroids has defined taxonomic classes (19) that may correspond to different mineralogical compositions, most of which have meteoritic analogues. Our color indices (B-R = 0.083 $\pm$ 0.070, V-R = 0.058 $\pm$ 0.055, and R-I = 0.088 $\pm$ 0.053, with solar colors subtracted) reveal a neutral reflectance spectrum that excludes all classes except six (B, C, F, G, D, P) that are associated with mixtures of carbonaceous material and mafic silicates, and one (M) that corresponds to NiFe metal or to mixtures of metal and spectrally neutral silicates. Our p_{v} interval encompasses all values for asteroids with unambiguous B, G, or M classifications and about half of the values for asteroids with unambiguous P, F, D, or C classifications.

The asteroid's composition is also constrained by (i) comparison of its radar reflectivity with values for asteroids whose taxonomic classes are known, and (ii) implications of its reflectivity for its surface bulk density. The asteroid's OC radar cross section (25 ± 10 m^2), its SC/OC ratio, and our D_{eff} interval bound its radar albedo $\hat{\sigma}$ (that is, radar cross section divided by $\pi D_{eff}^2/4$) in the OC and total-power (T = OC + SC) polarizations: $0.012 \leq \hat{\sigma}_{OC} \leq 0.11$ and $0.018 \leq \hat{\sigma}_T \leq 0.17$. The means and standard deviations of $\hat{\sigma}_T$ for radar-observed main-belt asteroids (20) are 0.10 ± 0.06 for nine objects classified B, G, F, or P; 0.17 ± 0.05 for eight C objects; and 0.32 ± 0.12 for four M objects. Among NEAs for which $\hat{\sigma}_T$ has been measured, it equals 0.10 and 0.18 for the two C objects and 0.63 for the sole M object. Thus 1998 KY26's radar albedo is consistent with B/C/F/G/D/P classification but not with M classification.

For a smooth sphere, $\hat{\sigma}_{SC}$ would equal zero and $\hat{\sigma}_{OC}$ would equal R, the smooth-surface reflection coefficient, which for materials of asteroidal interest depends primarily on surface bulk density d. For a target with a nonspherical shape or with moderate surface roughness at scales much greater than the wavelength, one could write: $R = \hat{\sigma}_{OC}/g$, where plausible values of the backscatter gain g are between 1.0 and 1.5. With wavelength-scale roughness, some echo power would be shifted to the SC polarization, and only part of the OC power would arise from smooth-surface echoes. For 1998 KY26, such roughness is present and the shape is not perfectly spherical. In this situation, the upper bound on the total-power albedo can be taken as an upper bound on R, and the corresponding value of $d(R)$ can be taken as an upper bound on the surface's average bulk density. The most widely used empirical relation for $d(R)$ (21) predicts $d(R = 0.17) = 2.8$ g cm^{-3}. Meteoritic analogs of M-class asteroids include irons and enstatite chondrites, which have mean specific gravities of 7.6 and 3.6 g cm^{-3}, respectively. C/B/G/F asteroids appear analogous to CI1/CM2/CM3 carbonaceous chondrites (22), which are primitive, unmelted, volatile-rich samples of solar nebula condensates (23) and whose mean specific gravities (2.2 to

2.9 g cm^{-3}) bracket our upper limit on *d*, supporting identification of 1998 KY26 as carbonaceous chondritic. (D/P asteroids lack meteoritic analogues and may resemble cosmic dust.)

Our optical and radar measurements reveal an unelongated, monolithic, several-decameter-wide, carbonaceous-chondritic body in a rapid spin state. This combination of characteristics is unique among known objects and sets boundary conditions on theories for the collisional and rotational evolution of individual asteroids and the population as a whole. Asteroids the size of 1998 KY26 are expected to have life times against catastrophic disruption of 10^7 to 10^8 years (24); carbonaceous chondrites are the weakest meteorites, so the short end of that interval probably applies here. Therefore this object may be a nonprimordial collision fragment derived from cratering or destruction of a larger asteroid (25). Many asteroids larger than a few hundred meters are thought to be porous, nearly strengthless "rubble piles" (26). The size distribution of monolithic subunits in rubble-pile asteroids is unknown, but the existence of 1998 KY26 establishes that they extend at least up to several-decameter sizes.

How did this asteroid's fast spin originate? Laboratory impact experiments (27) have shown that rapid rotations are common among spall fragments thrown out from the surface layer surrounding the impact site and that these fragments acquire their spins in the impact-generated shear field (28). However, the applicability of experiments on basaltic centimeter-sized targets to carbonaceous chondritic targets 10000 times larger is not known. Novel approaches to computer simulation of collisions (29) may shed light on the source of 1998 KY26's rotation and on how unique it might be among similar-sized collision fragments.

References and Notes

1. D. L. Rabinowitz, *et al.*, *Nature* **363**, 704 (1993).
2. D. L. Rabinowitz, E. Bowell, E. Shoemaker, K. Muinonen, K., in *Hazards Due to Comets and Asteroids*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1994). pp. 285-312.
3. Spacecraft flybys have imaged four asteroids, all with average dimensions between 14 and 58 km.
4. R. Greenberg, M. C. Nolan, W. F. Bottke, R. A. Kolvoord, J. Veverka, *Icarus* **107**,84 (1994); R. Greenberg *et al.*, *Icarus* **120**,106 (1996); J. Veverka et al., *Science* **278**, 2109 (1997).
5. G. V. Williams, *Minor Planet Electronic Circular 1998-L02* (1998).
6. Using simple expressions [E. M. Shoemaker and E. F. Helin, in *Asteroids: An Exploration Assessment*, D. Morrison and W. C. Wells, Eds. (NASA C. P. 2053, 1978) pp. 245-256] for the accelerations needed to leave low-Earth orbit and rendezvous with an asteroid, we find that for 1998 KY26 (a = 1.23 AU, e = 0.20, i = 1.5°), the total required change in velocity (delta-v) is 4.2 km s^{-1}. A lunar rendezvous requires 6 km s^{-1}.
7. We used B, V, R, and I color filters, with respective average wavelengths of 440, 550, 700, and 880 nm; H. Karttunen, P. Kröger, H. Oja, M. Poutanen, K. J. Donner, *Fundamental Astronomy* (Springer-Verlag, Berlin, 1987), p. 93.
8. The physical range extent typically is about twice the visible range extent. R. S. Hudson and S. J. Ostro, *Science* **270**, 84 (1995); A. K. Andrews, R. S. Hudson, D. Psaltis, *Optics Letters* **20**, 2327 (1995).
9. 1998 KY26's period was determined unambiguously in independent data from three different stations (Ondřejov, Table Mountain, Spacewatch). Observational techniques and data reduction procedures were similar to those described by P. Pravec, L. Šarounová, M. Wolf, *Icarus* **124**, 471 (1996), and by D. Rabinowitz, *Icarus* **134**, 342 (1998), and used an implementation of the Fourier method developed by A. W. Harris *et al.*, *Icarus* **77**, 171 (1989).
10. Rotation periods of near-Earth asteroids and similar-sized, main-belt asteroids average about 12 and 7 h, respectively [D. F. Lupishko and M. DiMartino, *Planet. Space Sci.* **46**, 47 (1998)].
11. The period of 1995 HM has been suggested to be 97.2 or 145.8 min by D. I. Steel, R. H. McNaught, G. J. Garradd, D. J. Asher, A. D. Taylor, *Planet Space Sci.* **45**, 1091 (1997).
12. A. W. Harris, *Lunar Planet. Sci.* **27**, 493 (1996).
13. The minimum required tensile strength T for an object of bulk density ρ is of order $\pi^2 D^2 \rho / 2P^2$. For this asteroid, T is less than 10^4 dyne cm^{-2}, which is less than 10^{-4} times values for meteorites and terrestrial rocks [J. Suppe, Principles of Structural Geology (Prentice-Hall, Englewood Cliffs, New Jersey, 1985), p. 155]. Thus 1998 KY26 could be held together by very meager bonds.
14. D. L. Mitchell, R. S. Hudson, S. J. Ostro, K. D. Rosema, *Icarus* **131**, 4 (1998).
15. L. A. M. Benner et al., *Icarus* **137**, 247 (1999), and *Icarus* **130**, 296 (1997).

16. For nominal relative velocities of 5 to 10 km s^{-1}, millimeter-sized (0.01-gram) meteoroids would create pits with diameters of order 1 cm, probably surrounded by a spall zone in which rock has been shattered and/or removed [D. E. Gault, F. Horz, J. B. Hartung, *Proc. Third Lunar Sci. Conf., Supp.* **3**, *Geochim. Cosmochim. Acta* **3**, 2713 (1972)]. The flux of 1-mm meteoroids, of order 10^{-12} m^{-2} s^{-1} in the inner solar system [E. Grun, H. A. Zook, H. Fechtig, R. H. Giese, *Icarus* **62**, 244 (1985)] but perhaps an order of magnitude higher in the main belt [D. S. McKay, T. D. Swindle, R. Greenberg, in *Asteroids II*, R. P. Binzel, T. Gehrels, M. S. Matthews, Eds. (Univ. Arizona Press, Tucson, 1989), pp. 617-642], would have roughened much of the asteroid in 10^7 years.

17. We conservatively assume a slope parameter, $G = 0.15 \pm 0.2$, for the asteroid's brightness as a function of solar phase angle.

18. We use the relation: $\log p_v = 12.247 - 2 \log D_{eff} - 0.4\ H$, where D_{eff} is in meters; E. F. Tedesco, G. J. Veeder, J. W. Fowler, J. R. Chillemi, *Tech. Rep. PL-TR-92-2049* (Phillips Laboratory, Hanscom AFB, Massachusetts, 1992).

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20. C. Magri, *et al.*, *Icarus* **140**, in press (1999).

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23. J. Lewis, *Physics and Chemistry of the Solar System* (Academic Press, San Diego, 1997).

24. R. Greenberg and M. C. Nolan, in *Resources of Near-Earth Space*, J. Lewis, M. S. Matthews, M. L. Guerrieri, Eds. (Univ. of Arizona Press, Tucson, 1993), pp. 473-492.

25. It has been suggested that tidal disruption of rubble-pile asteroids during close planetary encounters might generate large numbers of several-decameter objects [W. F. Bottke, Jr., D. C. Richardson, P. Michel, S. G. Love, *Planet. Space Sci.* **46**,311 (1998)], but such a process seems unlikely to produce ultra rapid fragment rotation.

26. S. G. Love and T. J. Ahrens, *Icarus* **124**, 141 (1996).

27. A. Fujiwara and A.Tsukamoto, *Icarus* **48**, 329 (1981).

28. Other laboratory experiments indicate that collisionally ejected fragments initially possess excited (non-principal-axis) spin states [I. Giblin and P. Farinella, *Icarus* **127**, 424 (1997)]. Our data show no evidence for non-principal-axis rotation, but this is not surprising given that the timescale for rotational relaxation of an object with 1998 KY26's size and spin period [A. W. Harris, *Icarus* **107**, 209 (1994)] is only of order 10^5 years, much less than the ~3 x 10^7 year dynamical lifetime of objects in Earth-crossing orbits.

29. E. Asphaug *et al.*, *Nature* **393**, 437 (1998).

30. Part of this research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA). Work at Washington State was supported in part by NASA's Planetary Geology and Geophysics Program. Work at Ondřejov *was* supported by the Grant Agency of the Academy of Sciences of the Czech Republic.

Figure Captions

Fig. 1. Our strongest echo spectra from June 8, sorted into rotation-phase bins 30° wide. Our analyses used 15° bins. Each spectrum is a one-dimensional image equivalent to a scan of radar brightness measured through a slit parallel to the asteroid's projected apparent pole. The frequency resolution, 1 Hz, corresponds to a slit width of 1.8 m/ cos δ, with δ the subradar latitude. The rotation phase origin is at 1998 June 8.26.

Fig. 2. Composite lightcurve constructed for P = 10.7015 min from clear-filter photometry obtained at Ondřejov on June 2.0 (x) and June 3.0 (+) and at Spacewatch on June 5.3 (●). The magnitudes have been scaled so they correspond to geocentric and heliocentric distances of 1 AU and an Earth-asteroid-sun angle of 28.1°. The rotation phase origin is at 1998 June 5.30. The noise level of individual measurements, about 0.1 mag, reflects the asteroid's faintness and our short integration times (20 to 50 s). The lightcurve data are represented well by a fourth order Fourier series (solid curve).

Fig. 3. 1998 KY26's shape estimated from least-squares fitting of a 124-vertex polyhedral model to the echo spectra. The model solution depends on the subradar latitude δ, which is not known but probably was at least a few tens of degrees from the pole. This figure shows the solution for an equatorial view (δ = 0). The fractional topographic relief is fairly insensitive to δ. Principal axes of inertia are labeled x, y, and z (the pole).

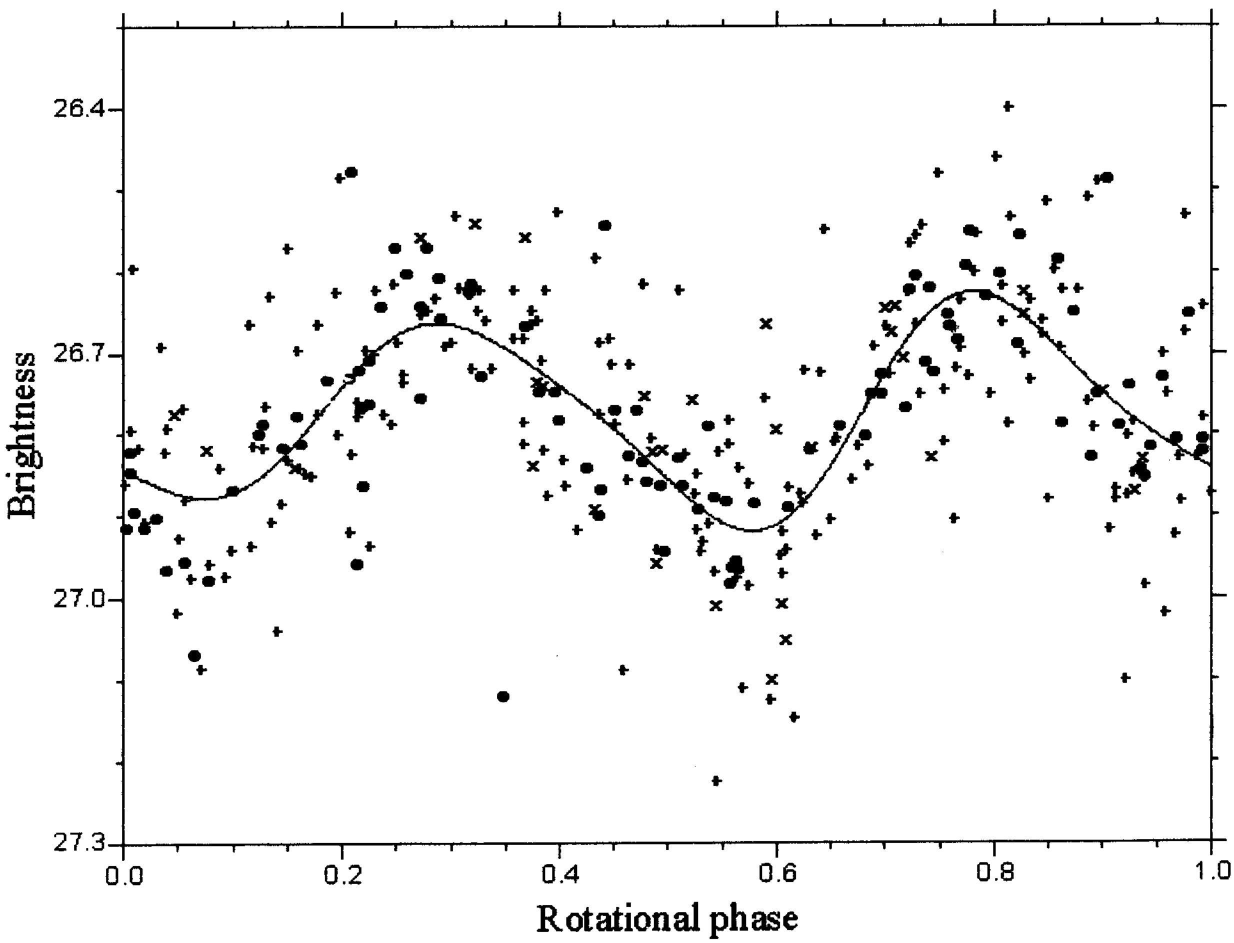
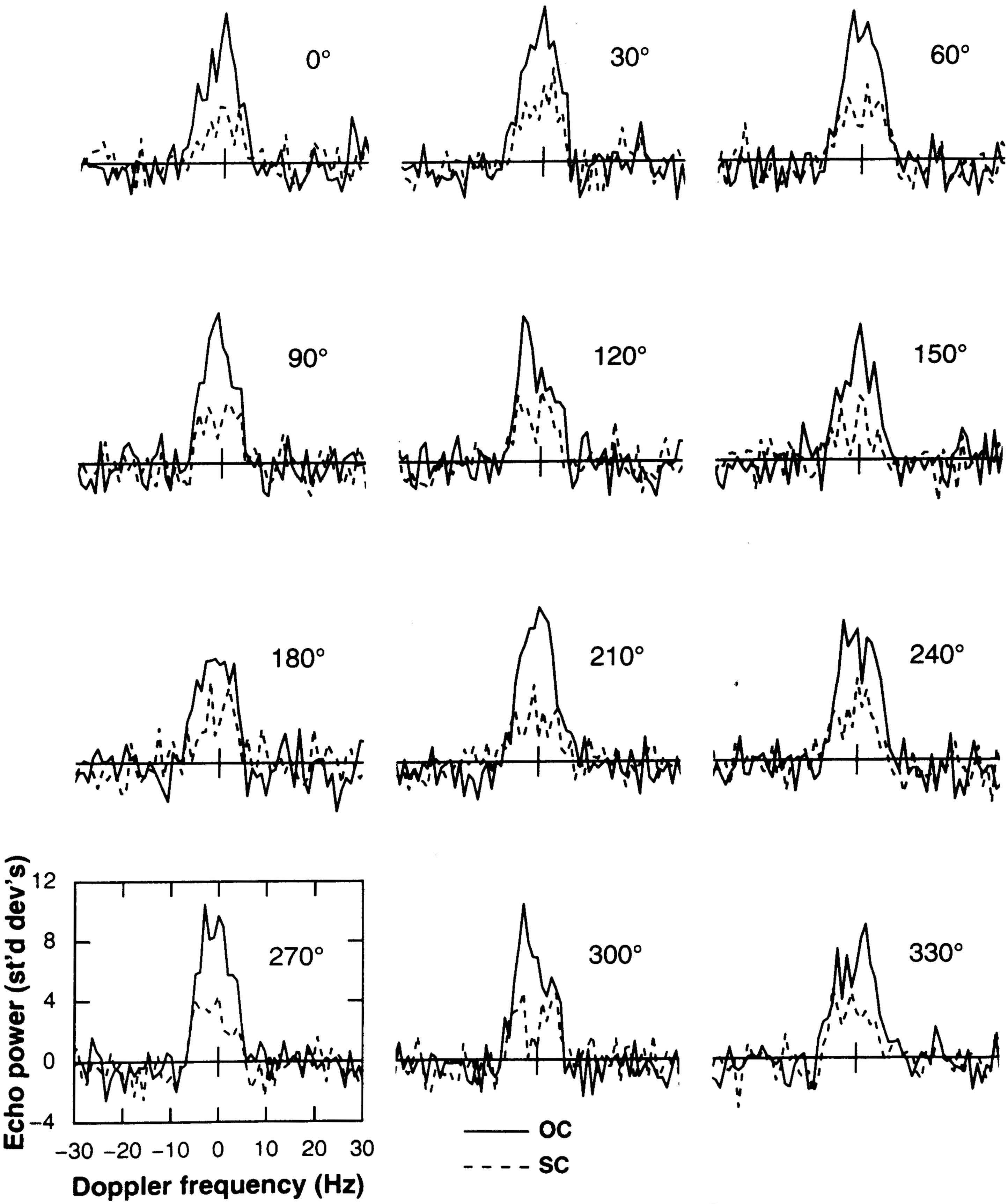


FIG 2

ASTEROID 1998 KY26

1998 JUNE 8

Goldstone echo power spectra



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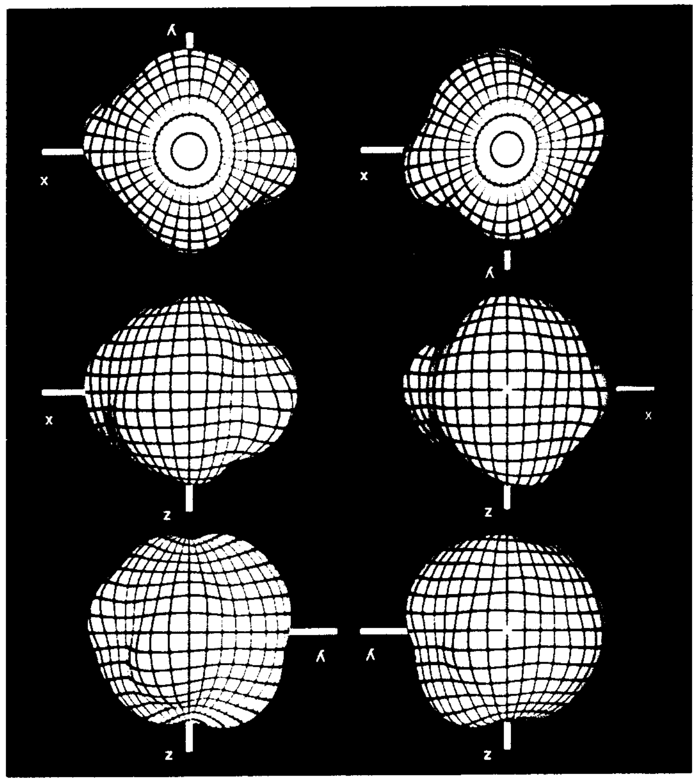

Ostro et al., **Fig. 3**